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Technical Report
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LES-8/9 Spectrum-Survey Techniques

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5 October 1990

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

Prepared for the Department of the Air Force
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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Hugh L. Southall

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

LES-8/9 SPECTRUM-SURVEY TECHNIQUES

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Group 64

TECHNICAL REPORT 888

5 OCTOBER 1990

LEXINGTON MASSACHUSETTS

ABSTRACT

Techniques for surveying the electromagnetic spectrum using communications satellites as sensors are discussed. The techniques presented are based on the use of tunable (by ground command) frequency synthesizers carried on Lincoln Experimental Satellites 8 and 9 (LES-8/9). The frequency synthesizers are used for the first-downconversion local oscillator in the satellite uplink receiver. Repetitive commanding of these synthesizers combined with on-board selectable filter bandwidths, signal power detectors, and a high telemetry data rate are shown to constitute an effective spectrum analyzer. Interpretation and presentation of collected data are also discussed.

This work was first reported at the Fourteenth Meeting of The Technical Cooperation Program (TTCP), Subgroup-S (Communication Technology and Information Systems) Technical Panel STP-6 (Space Communications) held at the Communications Research Centre, Ottawa, Canada, 26-30 January 1987.

ACKNOWLEDGMENTS

The authors wish to thank Fred Morton, Ted Sarantos and Al Richard of the Lincoln Experimental Satellite Operations Center (LESOC). They controlled the satellites and collected the data. We also thank Jim Will and Malcolm Coley for processing the survey data and Ellen Swenson for developing the telemetry-processing program.

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1. INTRODUCTION

As far back as 1967-1968, Lincoln Laboratory was interested in surveying the UHF electromagnetic spectrum from space. With the help of special on-board RFI receivers built by the Aerospace Corporation, Lincoln Experimental Satellites 5 (1967) and 6 (1968) carried out RFI surveys [1, 2]. Following in this tradition, the LES-8/9 satellites can also be used for surveying or scanning the electromagnetic spectrum. The complexity and flexibility of the LES-8/9 spacecraft permit the experiments to be carried out without the need for separate RFI-measurement receivers (as was the case for LES-5 and 6).

The on-board complexity of LES-8/9 gives many options in the collection and processing of the spectrum-survey data. This report deals only with those options actually implemented by Lincoln Laboratory. Other interesting possibilities are pointed out but are not discussed in detail. No attempt has been made to list all possibilities.

2. OVERVIEW OF OBSERVATION TECHNIQUES

Two distinct observation techniques are available:

1. Measurement of satellite received power level, reported by telemetry (Figure 1).
2. Transponding of the satellite received signal, allowing possible demodulation of the downlink signal (Figure 2).

It is also possible to combine 1 and 2 for simultaneous data collection and processing. Fixed-frequency or swept-frequency surveys may be used with either technique. Different satellite receiver bandwidths are also available for use with either technique.

These techniques are not restricted to UHF uplink frequencies. They are equally applicable at the LES-8/9 EHF-band uplink frequencies as well. At EHF-band, the steerable dish antenna can be employed to survey specific geographic locations, or a substantial portion of the visible Earth can be surveyed with the selection of the Earth-coverage horn antenna.

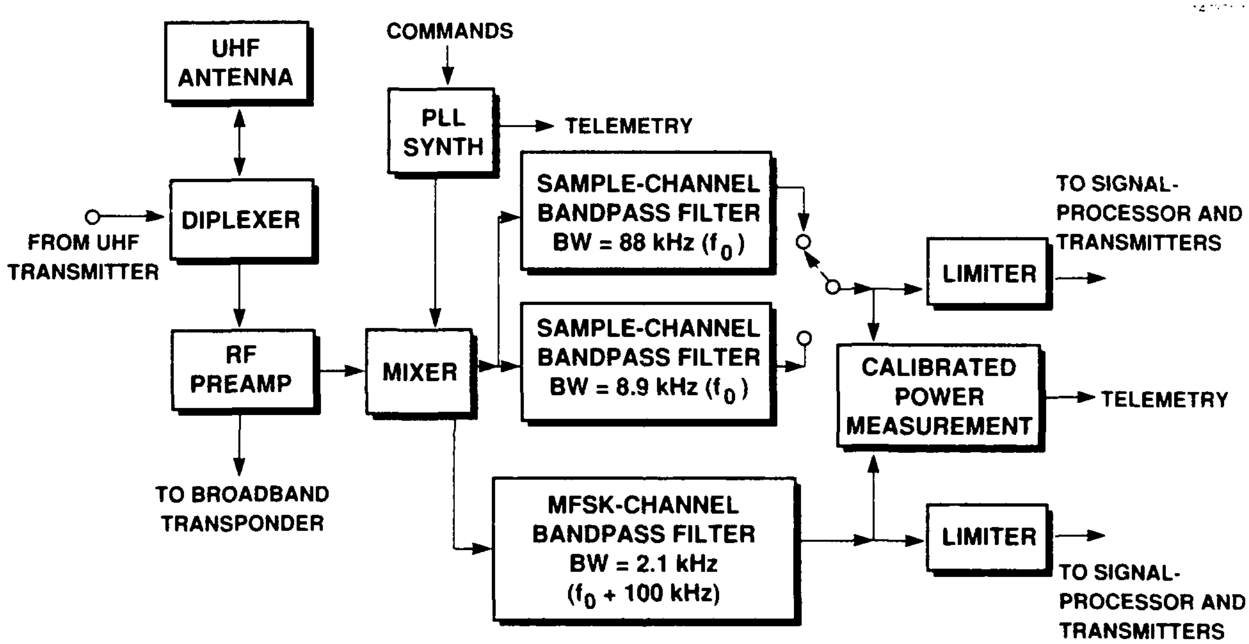

Figure 1. UHF spectrum survey by LES-8/9.

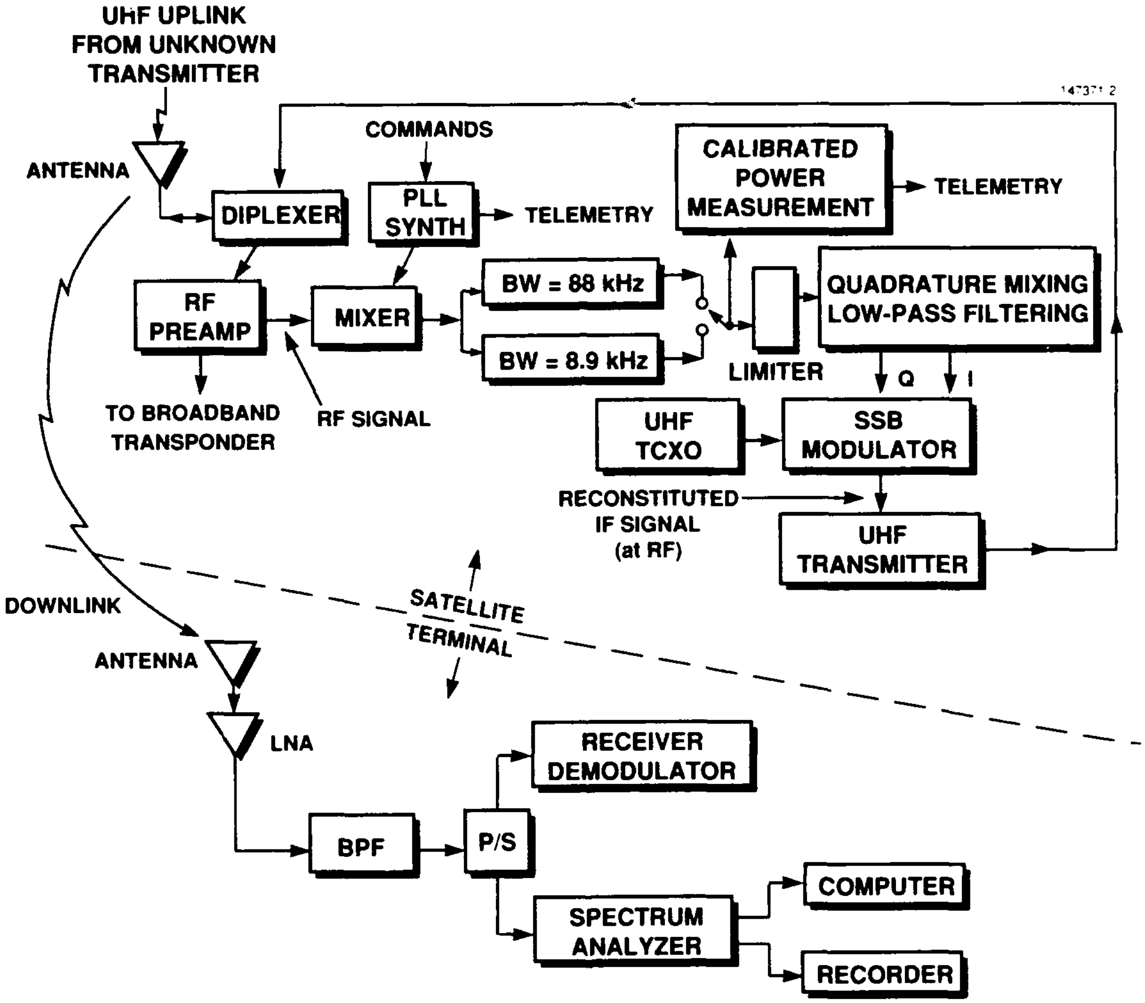

Figure 2. Transponding of satellite received signal.

3. SPACECRAFT HARDWARE AND TELEMETRY RECORDING

The key to a meaningful RFI-measurement experiment using LES-8/9 is the on-board Phase-Locked-Loop (PLL) Synthesizer (Figures 1 and 2), which can be commanded from the ground to stop at virtually any frequency in its tuning range. There are three channel bandwidths in which received power can be measured. They are 2.1-kHz, 8.9-kHz, and 88-kHz which are measured at the 3-dB-down points. The 2.1-kHz channel cannot be switched out and is always listening. The 8.9-kHz and 88-kHz channels are selectable by ground command and are mutually exclusive. There are two telemetered on-board signal-power detectors. One is dedicated to the 2.1-kHz channel. The second detector measures the power in the selected 8.9-kHz or 88-kHz channel. The high-rate telemetry available from LES-8/9 reports the power measured by both detectors once every 0.64 s. Low-rate telemetry is also available and provides an update interval of 64 s. The data received using low-rate telemetry are very coarse and are usable only for very long-term measurements. Lincoln Laboratory generally does not use this mode for this type of experiment. At UHF, the received frequency of the 2.1-kHz MFSK channel is 100 kHz higher than that of the 8.9-kHz or 88-kHz sample channel.

The command-tunable nature of the receiver can enhance the data collection to a high degree. By employing a computer to automatically generate synthesizer commands, the LES-8/9 satellites can be effectively used as spectrum analyzers in orbit. Lincoln Laboratory currently has a program which will allow us to set the start frequency, stop frequency, step size, and number of scans. The step size is generally set at 1.5625 kHz. This is the closest single command bit available without exceeding the 2.1-kHz MFSK-channel bandwidth. Once started, the program is left on its own until the scan is finished. Telemetry is supplied to the command computer; the program checks to see if all commands are executed. If a command misses, the computer continues to retry unless aborted by an operator. This implies that an occasional check of the computer is required. However, there have been few missed commands. Because of the low failure rate of the automatic command system, Lincoln Laboratory has accomplished 12-h unattended scans (repeated scans of the same frequencies) with good results.

When a scan is in progress, a second telemetry computer (normally the backup) is pressed into service. Only those telemetry points necessary for processing the scan data are recorded on the second computer. This saves substantial post-processing time by not having to search out specific words from the entire telemetry format. The one caveat is that in order to receive high-rate telemetry the 10- or 30-ft-diam. antenna at Lincoln Laboratory, Lexington, MA, must be used. As standard operational procedure, Lincoln Laboratory does not leave the 30-ft-diam. antenna unattended during operation in inclement weather. The 10-ft-diam. antenna was recently enclosed in a radome. It now has all-weather capability.

There are other possibilities for more sophisticated programs. Such programs might involve changing bandwidths (8.9- or 88-kHz back and forth during a scan). Sequentially scanning more than one band is also a possibility. Lincoln Laboratory has not implemented either of these possibilities and prefers to rely on the current simple and dependable program.

The medium- and narrow-band transponding functions can also be used to gather spectrum-survey data. Figure 2 shows some of the possible ways this might be accomplished. The downlink signal may be fed directly into a spectrum analyzer for real-time analysis. The video and sweep outputs from the analyzer may then be fed to an oscillographic recorder for a permanent record. The recorder may be used to obtain a real-time waterfall display of the incoming spectrum. The intensity modulation available on this type of recorder may be used to enhance the waterfall display or to create a different display, where intensity represents received downlink power. If the analyzer is remotely controllable, then data can be collected by computer for analysis. It is also possible to use the same computer for satellite and spectrum-analyzer control. Lincoln Laboratory has not implemented either of the last two options. There are a number of caveats in this type of data recording.

The downlink signal received in the medium (32-kHz)* and the narrow (5.3-kHz)* transponding modes will not be exact translations of the uplink received signal because of the hard limiting and filtering of the I and Q baseband signals before remodulating for transmission (Figure 2). The major effects of these operations are to eliminate any amplitude modulation from the signal and to bandlimit the signal.

Minor effects are to corrupt the downlink with TCXO-carrier leakage from the remodulation process, along with introducing frequency drifts due to temperature (also from TCXO). While these effects are not desirable for signal analysis, they have little impact on spectrum surveying, where frequency use is the important parameter. The downlink doppler shift is the final error introduced in the transponding mode. The CW TCXO leakage signal may have some value in that the frequency of the TCXO is so close to the actual downlink signal frequency that their doppler shifts can be considered to be equal. For most cases, this is an excellent assumption. If the spectrum analyzer has signal-tracking capabilities, the TCXO leakage can be tracked. By tracking the TCXO leakage, the frequency errors (contributed directly by the TCXO and, to a good approximation, by downlink doppler shift) will be automatically removed. The remaining frequency error due to uplink doppler shift is not easily removed. However, it may be of some use in characterizing signals received in the survey.

* These bandwidths are narrower than those quoted earlier in the paper. The earlier bandwidths of 8.9 kHz and 88 kHz occur in the uplink receiver. The 5.3-kHz and 32-kHz bandwidths occur after baseband conversion, just prior to transmission.

4. TELEMETRY PROCESSING

The on-board power detectors were carefully calibrated prior to launch. Further in-orbit calibration and improved algorithms give an accuracy of ± 1.5 dB within the linear range of the detectors. The detectors have approximately a 30-dB range, of which the middle 20 dB is considered to be linear. The governing equation is:

$$\left(P_r + N_o B\right)_{dBmW} = \left(Detector\ Input\ Power\right)_{dBmW} - 106 - K1 - K2 - K3 \quad .$$

where

Detector input power is determined from telemetered data using a calibration curve determined prior to launch which converts voltage to power;

$K1$ = Incremental gain factor at midband in dB;*

$K2$ = Uplink-frequency-variation gain factor in dB (0 dB at midband);

$K3$ = Temperature-dependence gain factor in dB (0 dB at 0°C).

It is then possible to subtract out $N_o B$ (obtained by using prelaunch data or data from a test interval during which the signal was known to be absent) to obtain P_r. Lincoln Laboratory currently does not use this option.

Lincoln Laboratory instead continues the above calculation by invoking:

$$EIRP = \left(P_r + N_o B\right) - G_r + PL \quad ,$$

where

G_r = Satellite receive antenna gain in dBi

PL = Path loss in dB.

Because of the inclined orbits, the range to and antenna gain seen by a given transmitter change with time. Nominal values of 39,000 km for range and 10 dBi for the UHF antenna gain are used. An option in the program allows these values to be changed if the transmitter location is known. Note that the LES-8/9 UHF antennas are RHCP, which gives EIRP (RHCP). The results are slightly in error because of the degradation of the circular polarization on LES-8 [3,4]. On long-term scans, the portion of the Earth which is visible can change by a considerable amount due to the orbital inclination. Figure 3 shows the difference between the 24-h coverage (in which signal strength could be expected to remain constant) and the variable coverage (in which strength will vary with time).

The telemetry program which does the above calibration and calculation also controls the format of the data presentation. Again, there are a number of options.

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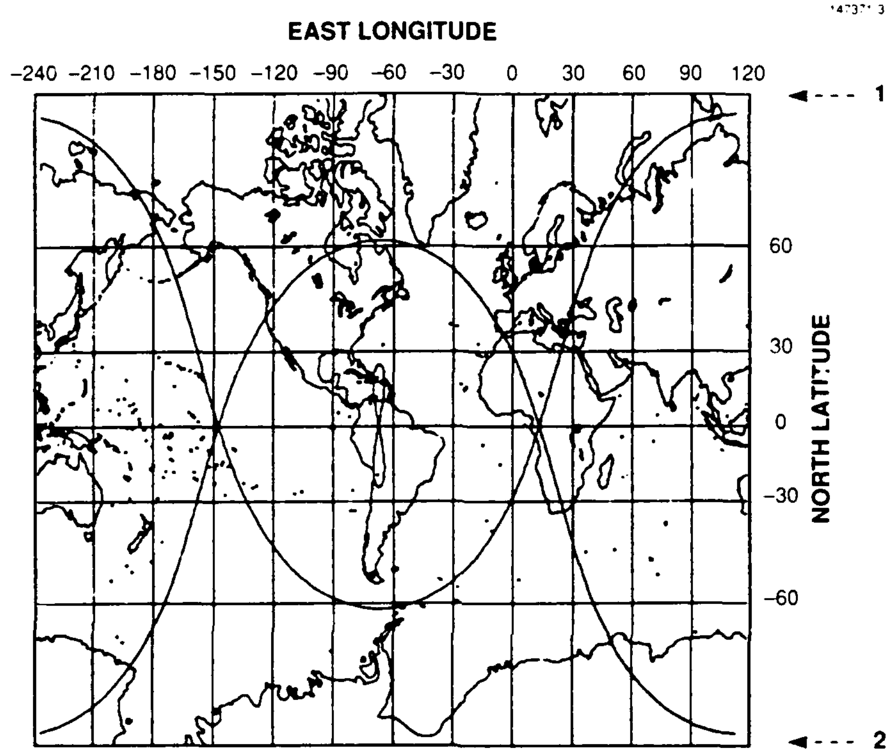
* The gain factor (106 dB) in the equation corresponds to the performance at midband of the EHF MFSK uplink channel in both LES-8 and LES-9. Each K1 is the difference between that reference gain and the midband gain of another channel. At UHF, there are 3 K1 values for each satellite, one for each channel. At UHF, there is a K2 for LES-8 and another for LES-9. A single K3 suffices for both.



SATELLITE POSITIONS FOR TERMINATOR CONTOURS

	LATITUDE	LONGITUDE
1	20.07°N	67.447°W
2	20.07°S	67.447°W

CONTOURS FOR 0° ELEVATION ANGLE, TRANSMITTER AT MEAN SEA LEVEL.

Figure 3. 24-h coverage LES-8. (LES-8 is stationkept between 60° and 70° west longitude.)

5. DATA PRESENTATION

The spectrum analyzer and oscillographic recorder shown in Figure 2 give records such as those shown in Figures 4, 5(a), and 5(b). Figure 4 is the spectrum-analyzer record and is included here for completeness and as an aid to understanding Figures 5(a) and 5(b). The waterfall records shown in Figures 5(a) and 5(b) are oscillographic records corresponding to Figure 4; the x- and y-axis outputs from the analyzer drive the x- and y-axes of the recorder. Therefore, the oscillographic records are in the same units as are those from the analyzer. The spacing between the traces is controlled by the recorder chart speed. In Figure 5(b) the analyzer's y-axis output is used to modulate the z-axis (intensity) of the recorder as well as its y-axis. In this case [Figure 5(b)] only signals above the z-axis cutoff level of the recorder appear on the record. Note that the stronger signals are darker and that most of the noise has been eliminated. These record types are excellent for interpretation by people. Subtle or long-term trends not easily recognizable by a simple computer program can be spotted by visual inspection. If long runs were to be made and data from the analyzer were collected by a computer, substantial processing time could be saved by knowing which time frames were most likely to be interesting. Interpretation of the visual record is a simple way to provide a best guess as to interesting times to process. Conversely the chart record can provide a coarse check of the computer's data analysis.

Survey data collected by telemetry have many options. Table 1, output data listing from processed telemetry, shows all the pertinent data that can be displayed. Current options allow the data to be plotted, printed, or dumped to magnetic tape. It is not likely that anyone would want to make use of the printed data. Lincoln Laboratory currently uses the printout option to check a small number of tape records after the tape has been written. This gives a higher confidence level for the tape record. The tape record is used for permanent data storage and for further analysis. For the small amount of spectrum scanning that Lincoln Laboratory has done, we usually select the plot option and visually inspect the data Figure 6 is a plot showing single-frequency monitoring over a two-hour period. The use and relative-power levels at that frequency are easily seen. The data have not been corrected for N_oB. It is possible to do this by hand directly from the plots. The value of N_oB can be obtained either from the plots directly or from prelaunch calibration data. It is also possible to obtain improved P_r/N_o estimates by measuring the received power in any two of the three available channels, thus cancelling out common sources of error. Example calculations removing N_oB are shown on the plot in Figure 6. The examples were done by taking the values directly from the plot.

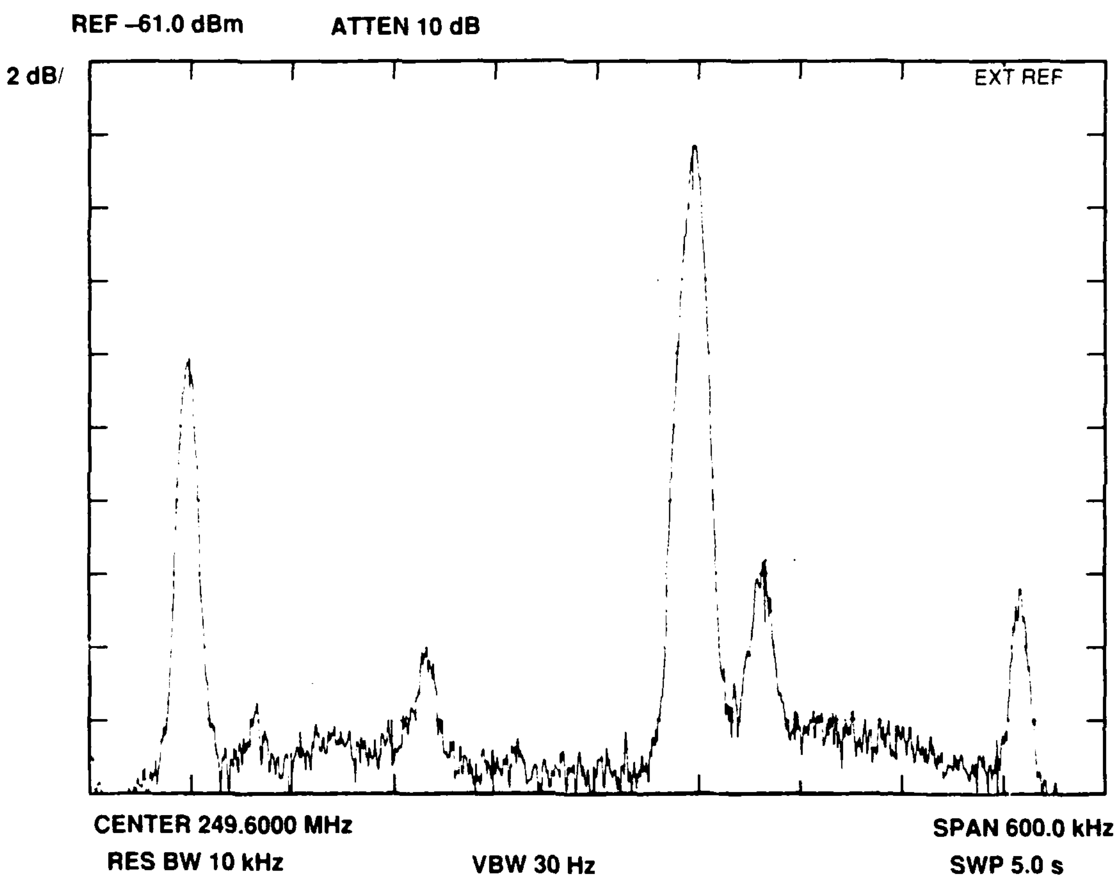
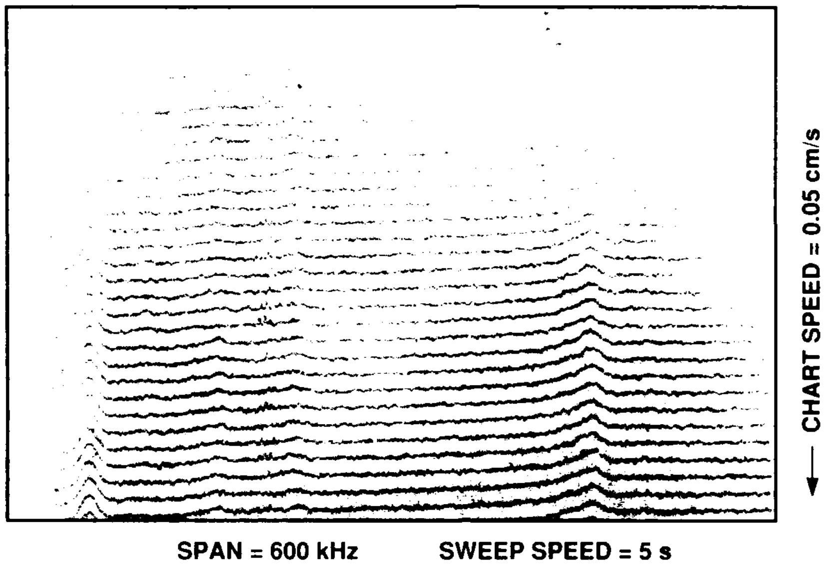
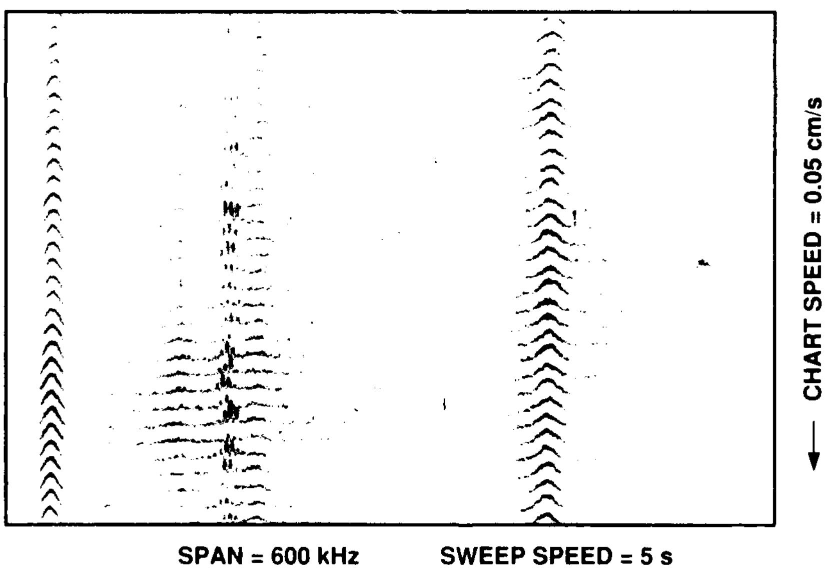


Figure 4. Spectrum-analyzer record.



(a)



(b)

Figure 5. (a) Oscillographic records, y-axis modulation. (b) Oscillographic records, y-axis plus z-axis modulation.

TABLE 1
Output Data Listing from Processed Telemetry

Date	Time (UTC)	MFSK (2.1-kHz BW) Frequency (MHz)	MFSK (2.1-kHz BW) Power (dBmW)	Sample Frequency (MHz)	Sample Power (dBmW)	Mode
83/ 3/15	5:14:53	337.6375	29.7123	337.5375	36.2005	U ST N
83/ 3/15	5:14:53	337.6375	29.1871	337.5375	37.8138	U ST N
83/ 3/15	5:14:54	337.6375	29.1847	337.5375	36.0026	U ST N
83/ 3/15	5:14:55	337.6375	29.7099	337.5375	37.0338	U ST N
83/ 3/15	5:14:55	337.6391	29.1815	337.5391	35.3577	U ST N
83/ 3/15	5:14:56	337.6391	28.5754	337.5391	35.8114	U ST N
83/ 3/15	5:14:56	337.6391	29.7091	337.5391	36.0213	U ST N
83/ 3/15	5:14:57	337.6391	29.1815	337.5391	36.2114	U ST N
83/ 3/15	5:14:58	337.6391	29.1815	337.5391	35.8120	U ST N
83/ 3/15	5:14:58	337.6406	28.5647	337.5406	35.5835	U ST N
83/ 3/15	5:14:59	337.6406	29.6983	337.5406	35.0991	U ST N
83/ 3/15	5:15: 0	337.6406	29.1737	337.5406	35.0997	U ST N
83/ 3/15	5:15: 0	337.6406	29.6989	337.5406	35.0997	U ST N
83/ 3/15	5:15: 1	337.6406	29.1737	337.5406	35.3499	U ST N
83/ 3/15	5:15: 2	337.6422	29.1308	337.5422	36.0073	U ST N
83/ 3/15	5:15: 2	337.6422	29.6554	337.5422	35.5797	U ST N
83/ 3/15	5:15: 3	337.6422	29.1302	337.5422	35.0953	U ST N
83/ 3/15	5:15: 4	337.6422	29.1308	337.5422	35.3461	U ST N
83/ 3/15	5:15: 4	337.6422	29.1308	337.5422	35.5803	U ST N
83/ 3/15	5:15: 5	337.6437	29.1895	337.5437	36.9423	U ST N
83/ 3/15	5:15: 5	337.6437	28.5810	337.5437	36.9423	U ST N
83/ 3/15	5:15: 6	337.6437	28.5810	337.5437	36.7841	U ST N
83/ 3/15	5:15: 7	337.6437	28.5810	337.5437	37.7547	U ST N
83/ 3/15	5:15: 7	337.6437	28.5816	337.5437	36.2581	U ST N
83/ 3/15	5:15: 8	337.6453	28.5739	337.5453	40.8076	U ST N
83/ 3/15	5:15: 9	337.6453	29.1811	337.5453	39.8302	U ST N
83/ 3/15	5:15: 9	337.6453	29.1811	337.5453	40.3072	U ST N
83/ 3/15	5:15:10	337.6453	29.1823	337.5453	41.4070	U ST N
83/ 3/15	5:15:11	337.6453	29.1823	337.5453	40.6655	U ST N
83/ 3/15	5:15:11	337.6469	29.1746	337.5469	50.2052	U ST N
83/ 3/15	5:15:12	337.6469	29.1746	337.5469	51.5805	U ST N

TABLE 1 (Continued)
Output Data Listing from Processed Telemetry

Date	Time (UTC)	MFSK (2.1-kHz BW) Frequency (MHz)	MFSK (2.1-kHz BW) Power (dBmW)	Sample Frequency (MHz)	Sample Power (dBmW)	Mode
83/ 3/15	5:15:12	337.6469	29.1740	337.5469	51.3396	U ST N
83/ 3/15	5:15:13	337.6469	29.1740	337.5469	49.9551	U ST N
83/ 3/15	5:15:14	337.6469	29.6991	337.5469	50.9402	U ST N
83/ 3/15	5:15:14	337.6484	29.1897	337.5484	51.1263	U ST N
83/ 3/15	5:15:15	337.6484	29.1915	337.5484	49.0566	U ST N
83/ 3/15	5:15:16	337.6484	29.1915	337.5484	50.9673	U ST N
83/ 3/15	5:15:16	337.6484	29.1897	337.5484	48.9413	U ST N
83/ 3/15	5:15:17	337.6484	29.1897	337.5484	52.0060	U ST N
83/ 3/15	5:15:18	337.6500	29.1852	337.5500	50.6502	U ST N
83/ 3/15	5:15:18	337.6500	29.7104	337.5500	50.2179	U ST N
83/ 3/15	5:15:19	337.6500	28.5774	337.5500	50.2185	U ST N
83/ 3/15	5:15:20	337.6500	29.1858	337.5500	50.6508	U ST N
83/ 3/15	5:15:20	337.6500	29.7110	337.5500	50.9548	U ST N
83/ 3/15	5:15:21	337.6516	28.5735	337.5516	49.7610	U ST N
83/ 3/15	5:15:21	337.6516	28.5730	337.5516	50.1776	U ST N
83/ 3/15	5:15:22	337.6516	28.5730	337.5516	51.1828	U ST N
83/ 3/15	5:15:23	337.6516	29.1820	337.5516	47.9751	U ST N
83/ 3/15	5:15:23	337.6516	29.1820	337.5516	48.3843	U ST N
83/ 3/15	5:15:24	337.6531	29.1938	337.5531	49.6151	U ST N
83/ 3/15	5:15:25	337.6531	29.1938	337.5531	44.4380	U ST N
83/ 3/15	5:15:25	337.6531	29.1938	337.5531	48.8277	U ST N

MODE

UPLINK	PLL SYNTH	BANDWIDTH*
U = UHF	ST = STOP	N = NARROW (8.9 kHz)
KH = K HORN	HL = HELP	M = MEDIUM (88 kHz)
KD = K DISH	HP = HOP	

* Bandwidth refers only to the sample channel

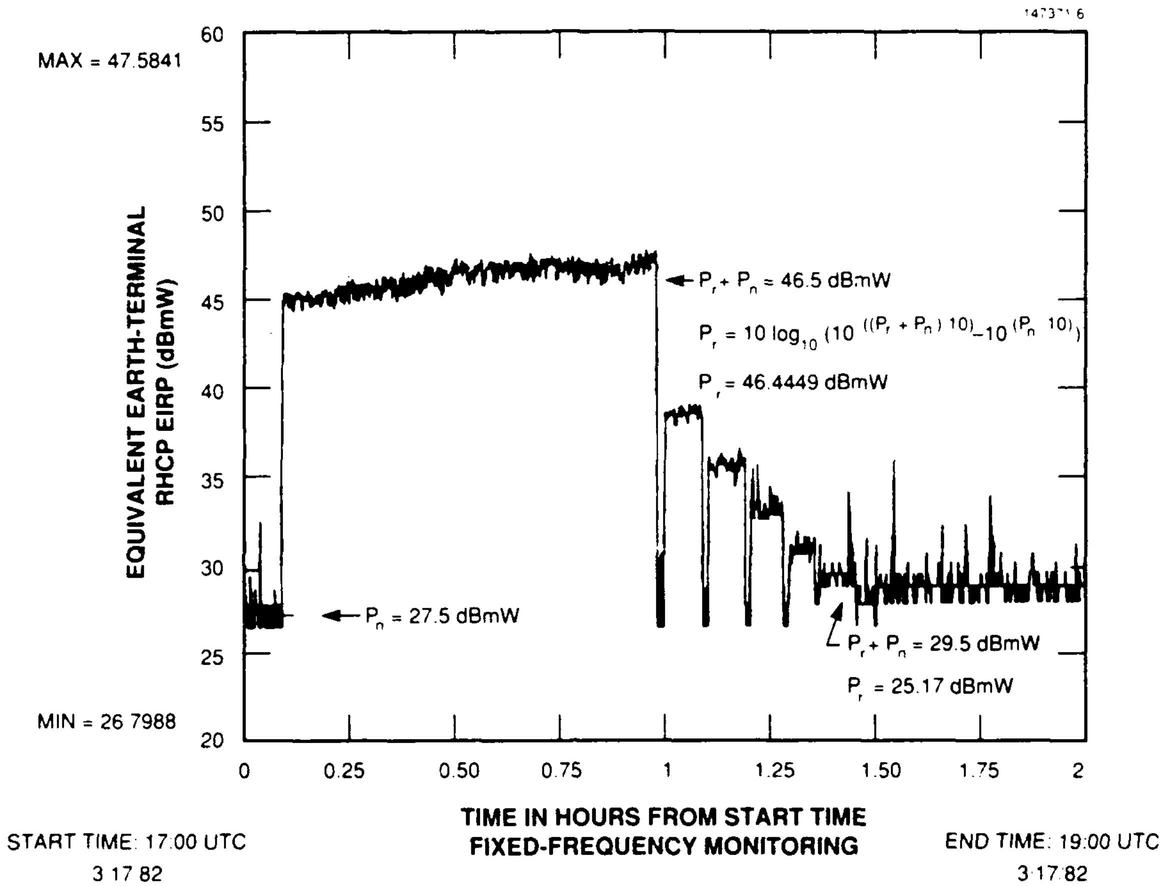


Figure 6. Power in LES-9 MFSK channel, 2.1-kHz bandwidth.

Step surveying is the most interesting of the satellite telemetry techniques. Figures 7, 8, and 9 are examples of this type of scan. Figure 7 is a plot of the center frequency of the uplink receiver vs time. This shows how the on-board synthesizer is stepped across a band of frequencies. Figures 8 and 9 are the signal-power plots in estimated EIRP (RHCP) for the MFSK and sample channels, respectively, for the frequencies in Figure 7. The step scan is very similar to a spectrum analyzer with the following settings:

Frequency Span	=	From fixed frequency (0-Hz span) to full range of satellite frequency synthesizer
Resolution Bandwidth	=	2.1 kHz minimum, 88 kHz maximum
Vertical Scale	=	Selectable dB per division
Sweep Time	=	Command rate x number of commands
Noise-Density Floor	=	– 4 dB (mW/Hz) equivalent RHCP from Earth terminal at nominal range.

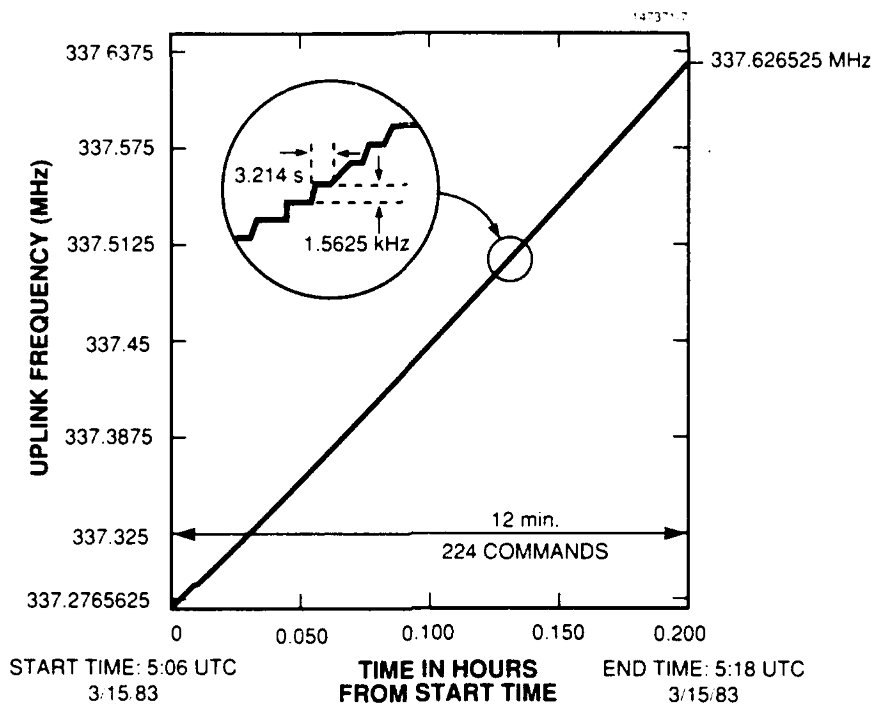


Figure 7. Received uplink frequency vs time, sample channel.

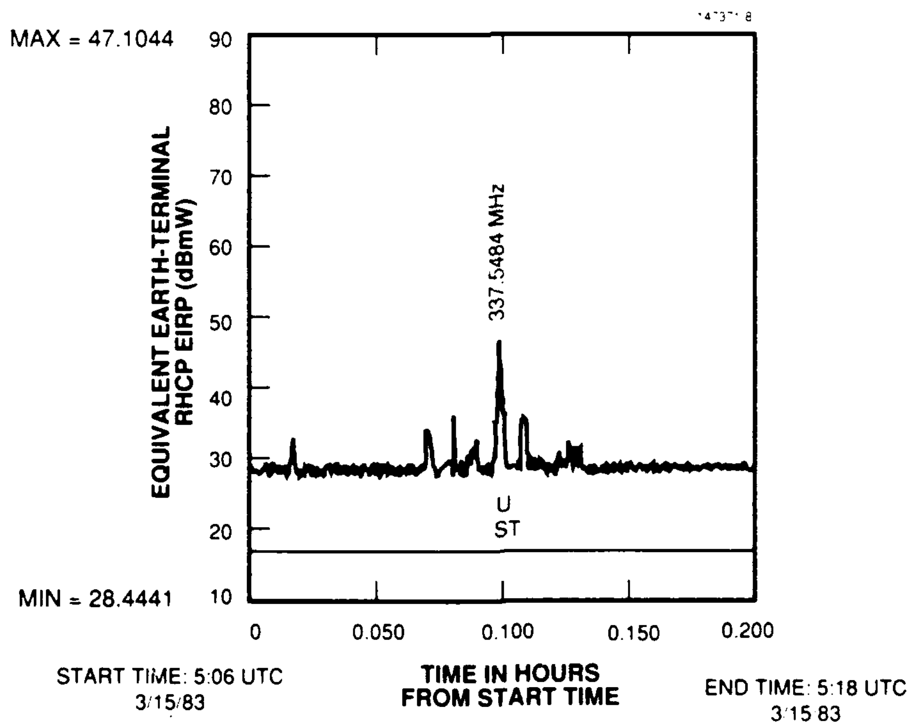


Figure 8. Power in LES-8 MFSK channel, 2.1-kHz bandwidth.

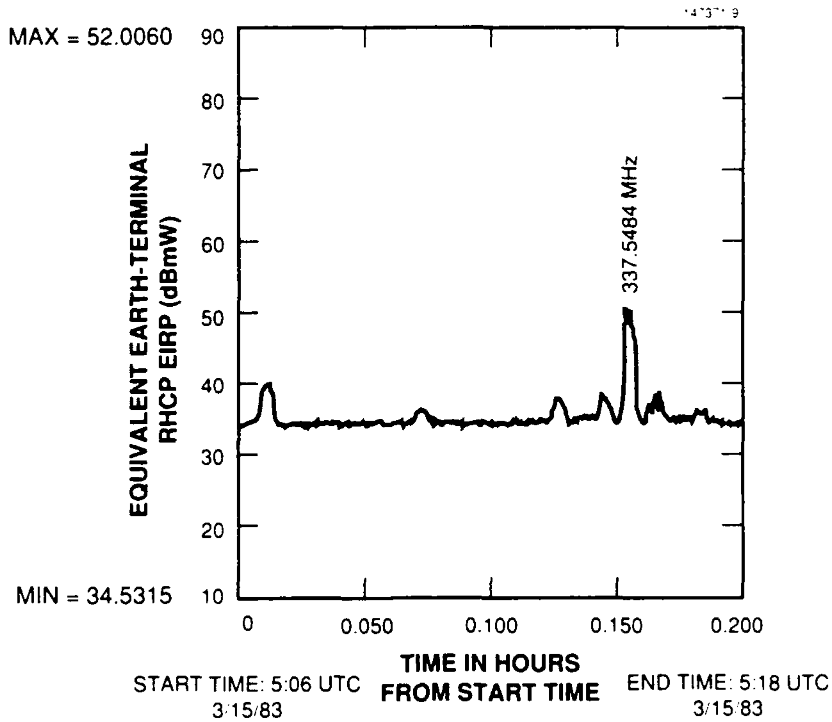


Figure 9. Power in LES-8 sample channel, 8.9-kHz bandwidth.

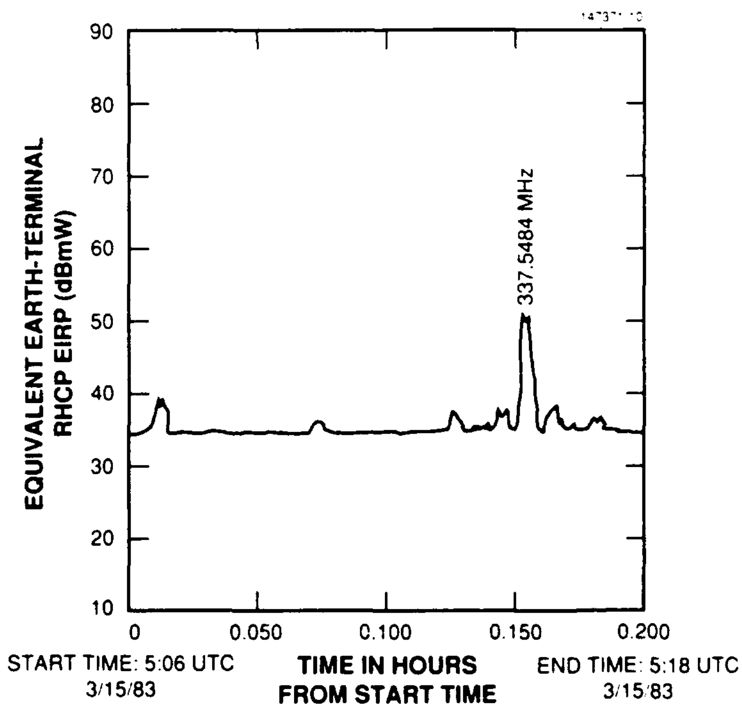


Figure 10. Average over 5 data points of power in LES-8 sample channel, 8.9-kHz bandwidth.

Bandwidths of 2.1, 8.9, and 88 kHz, frequency span, and frequency-step size are all selectable. The command interval of 3.214 s is fixed. Introduction of wait loops into the program could give longer dwell times at each step. It is also possible to plot amplitude vs frequency on one plot instead of amplitude or frequency vs time. Lincoln Laboratory does not have either of these options.

For low-power signals, telemetry quantization results in noisier data. In this case a sliding average can be applied to the processed data. In order to keep the program simple, only an odd number of points are allowed to be picked for averaging, so that the center time for the x-axis is always exact. Figure 10 is an averaged plot of the data presented in Figure 9. The worst uncertainty in the telemetry measurement happens at the extremes of the detector range. The detectors in the satellites saturate at high levels of received power. At low received-power levels the detectors have a variation of typically 3-dB peak-to-peak. Lincoln Laboratory averages over 5 points, which gives a 3-dB improvement. Fewer points averaged will not obtain the maximum improvement, and a larger number of points averaged will distort the data. This averaging is the equivalent of the video filter in a spectrum analyzer.

It is also possible to average complete scans together. We have not tried this and currently have no plans to do so. However, there is a caveat. If a desired frequency span took one hour to scan, then in the two hours needed to get two scans for averaging, the spectrum could change considerably. It would seem appropriate to do many small frequency-span scans over and over if this type of averaging is desired. If a large number of small scans of the same frequency span are done, the time base can again become long. For this case, a sliding average applied to complete scans instead of individual points seems appropriate.

GLOSSARY

BPF	Bandpass Filter
BW	Bandwidth
CW	Continuous Wave
EHF	Extremely-High Frequency
EIRP	Effective Isotropically Radiated Power
G_r	Satellite Receive Antenna Gain (dBi)
IF	Intermediate Frequency
LNA	Low-Noise Amplifier
MFSK	Multiple Frequency-Shift Keying
N_o	Noise-Power Density
N_oB	Noise Power in Bandwidth B
PL	Ground-Terminal-to-Satellite Path Loss
PLL	Phase-Locked Loop
P_r	Satellite Uplink Received Power
P/S	Power Splitter
RF	Radio Frequency
RFI	Radio-Frequency Interference
RHCP	Right-Hand Circular Polarization
SSB	Single-SideBand
TCXO	Temperature-Compensated Crystal Oscillator
UHF	Ultra-High Frequency

REFERENCES

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Techniques for surveying the electromagnetic spectrum using communications satellites as sensors are discussed. The techniques presented are based on the use of tunable (by ground command) frequency synthesizers carried on Lincoln Experimental Satellites 8 and 9 (LES-8/9). The frequency synthesizers are used for the first-downconversion local oscillator in the satellite uplink receiver. Repetitive commanding of these synthesizers combined with on-board selectable filter bandwidths, signal power detectors, and a high telemetry data rate are shown to constitute an effective spectrum analyzer. Interpretation and presentation of collected data are also discussed.

This work was first reported at the Fourteenth Meeting of The Technical Cooperation Program (TTCP), Subgroup-S (Communication Technology and Information Systems) Technical Panel STP-6 (Space Communications) held at the Communications Research Centre, Ottawa, Canada, 26-30 January 1987.

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LES-8/9 (LES-8, LES-9)	spectrum analyzers	spectrum utilization
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